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Status of JPL Lasercom R&D

H. Hemmati

CCSDS
Optical Comm Meeting
April 16-17 2012

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Earth-Orbiting Lasercom Terminal

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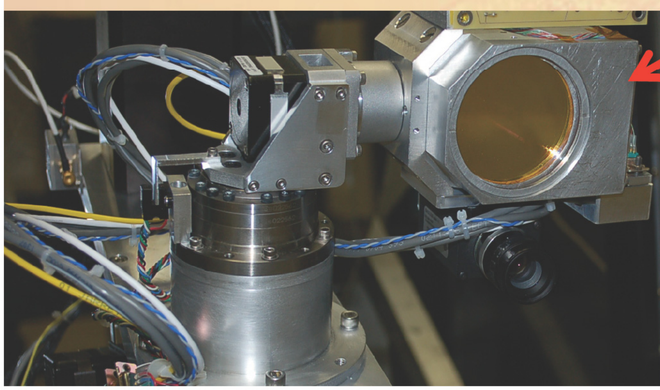
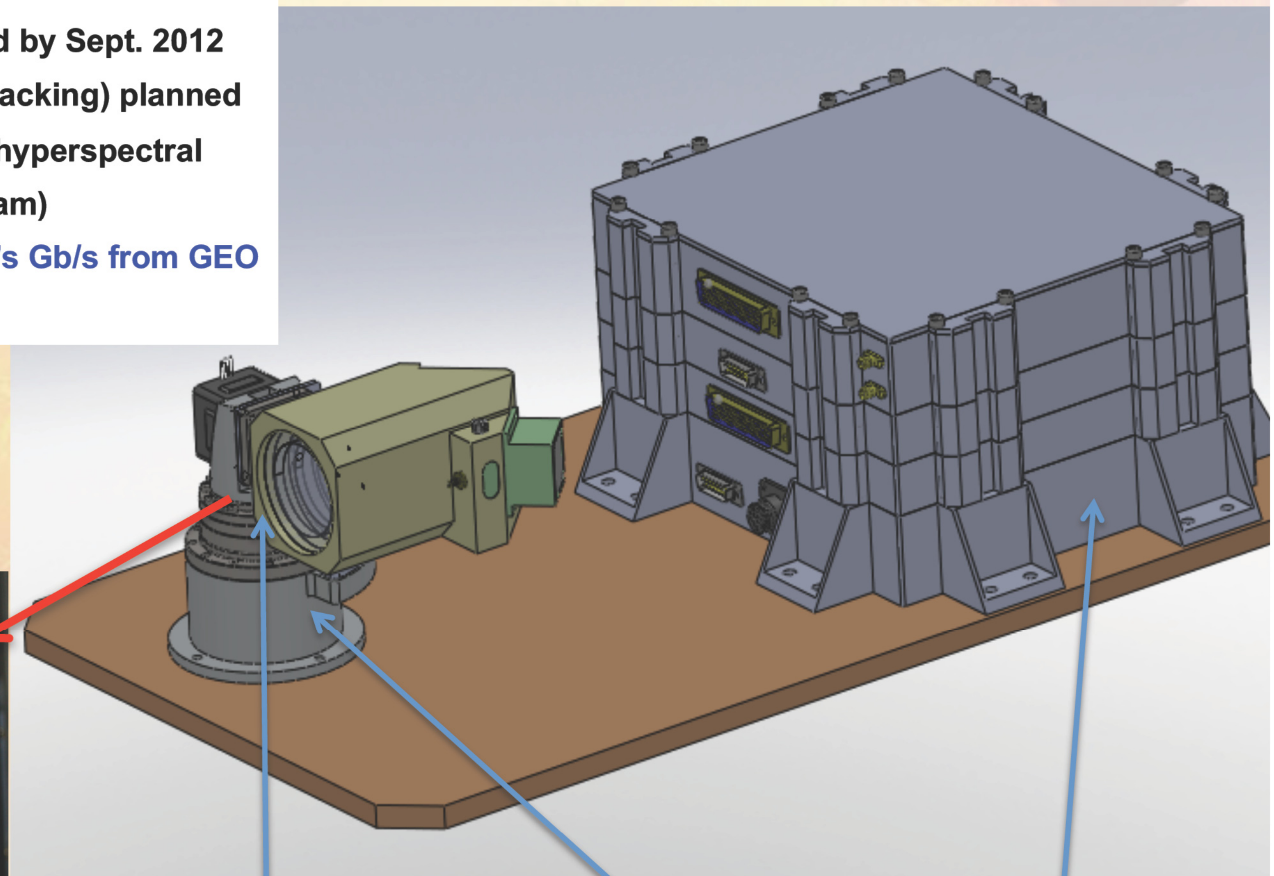
10 Gb/s Downlink From LEO Spacecraft

- Custom-developed (@ JPL)
    - Transmitter modem (Virtix-5 based)
    - Receiver-modem
    - High-precision 2-axis gimbal
    - Acquisition & tracking algorithm/software
- Near-Engineering Model to be developed by Sept. 2012
- Airplane test of system (acquisition & tracking) planned while transmitting SAR instrument and hyperspectral imager data to ground (DC8 & Gulf Stream)
- Scalable to >100 Gb/s from LEO, and 10's Gb/s from GEO
- Suitable for CubeSats





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Interplanetary Lasercom Technologies

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Challenges

Relative to near-Earth comm links:

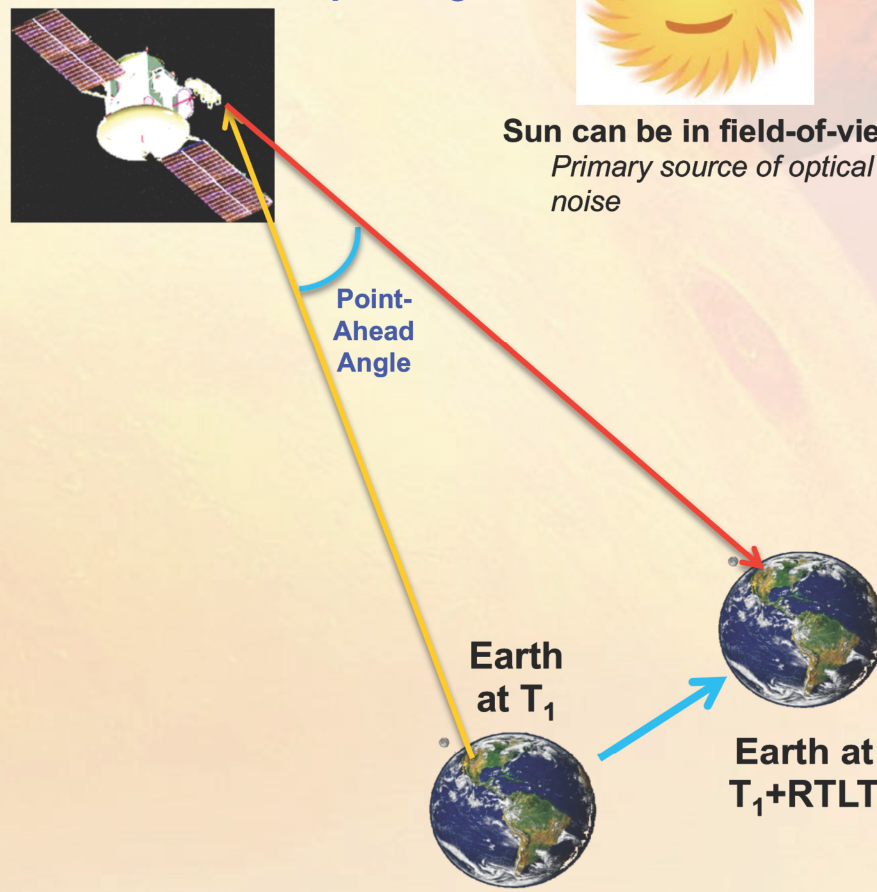
- **Pointing**: Must point downlink from Deep Space transceiver using a ~10,000X dimmer uplink beacon across 100X greater round-trip light time
  - *Requires improved spacecraft disturbance isolation to be able to acquire the dim beacon*
  - *Requires ultra-sensitive flight detector arrays for beacon tracking and point-ahead confirmation without handshaking*

- **Modulation**: Need high order (16 to 512) Pulse Position Modulation (PPM) and power-efficient multi-Watt lasers to overcome huge signal loss
  - *~10,000,000X greater loss at Mars far range than moon requires >300 W peak power lasers*
  - *Flight laser amplifier is largest power consumer*

- **Ground Detection**: Must shift burden away from flight terminal by using ≥10m diameter telescopes on Earth
  - *Requires large (~1 mm^2) photon counting detector arrays with high detection efficiency (>50% desired) behind telescope due to atmospheric blurring*

Large $1/R^2$ range-loss
Large $2R/c$ round-trip light time
Requires sub-micro-radian pointing

Sun can be in field-of-view
Primary source of optical noise



Requires:
- **Multi-kW power uplink lasers**
- **>10 m optical receiver apertures**
- **Efficient downlink detectors**

Technology Tall Tent Poles

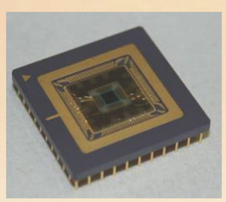
Spacecraft disturbance rejection platform
- 10,000X greater disturbance rejection than state-of-the-art
- *Goal of < 0.3 Hz break frequency for > 27 dB of disturbance rejection at 1.5 Hz*

Photon counting space receiver
- 10X higher sensitivity over state-of-the-art
- *Goal of -90 dBm at 1 Mb/s sensitivity*

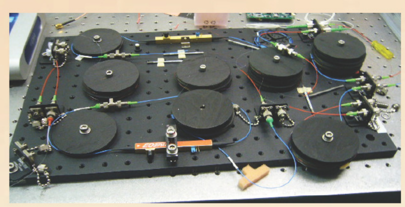
Efficient deep space PPM laser transmitter
- 2X efficiency improvement over state-of-the-art
- *Goal of > 20% efficiency with < 500 ps pulse width*

Ground receiver detector array and read-out for 5 to 12 meter ground telescopes
- 2X efficiency improvement over state-of-the-art
- *Goal of < 3 dB detection loss with > 5 m telescope*

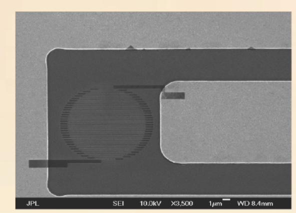
JPL hybrid active/passive strut with 50 dB isolation at 5 Hz (TRL 4)



Photon counting array, 1 pW/m^2 for 0.02 pixel centroiding error (TRL 3)



Part of JPL prototype laser transmitter for >20% efficiency (TRL 3)



JPL superconducting nanowire pixel (> 70% efficient, arrays are TRL 3)

Mission Analysis

- **Analyzed mission scenarios to improve understanding of diverse planetary optical comm needs:**
  - Operating points resulting from orbital geometries and effect on link conditions (range, sun-angles, range-rate and transverse velocity, contact time, gap-time)
  - Downlink data volumes achievable, as a function of number and distribution of ground stations

Mission Case	Planetary at Mars	Planetary at Jupiter	Planetary at Saturn	Astrophysics at L2	Heliophysics at L1
Reference mission	MRO	Juno	Cassini	THEIA with SFC	SDO Follow-On
Relative downlink performance	10x MRO Ka	>10x Juno Ka	10x Cassini X-band	10x JWST Ka	10x SDO Ka
Targeted downlink data-rate	267 Mb/s at 0.67 AU	2 Mb/s at 4.4 AU	0.16 Mb/s at 10 AU	1.5 Gb/s at 0.012 AU	1.5 Gb/s at 0.01 AU
Other key requirements	38 kg mass 110 W power	radiation solar noise	range solar noise	narrow slot widths	narrow slot widths solar noise
Flight telescop diameter	22 cm	40 cm	50 cm	< 22 cm	< 22 cm
Ground downlink telescope size	12 m	12 m	12 m	1 m	1 m
Ground uplink beacon power	5 kW	6 kW	10 kW	20 W	20 W
Outage due to SEP < 5°	< 1 month/ 2 years	Mission Dependent	< 1 month/year	None	None

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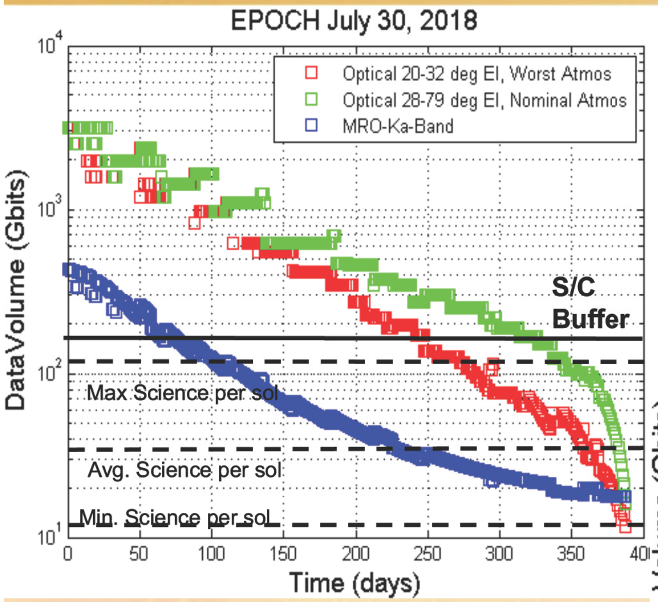
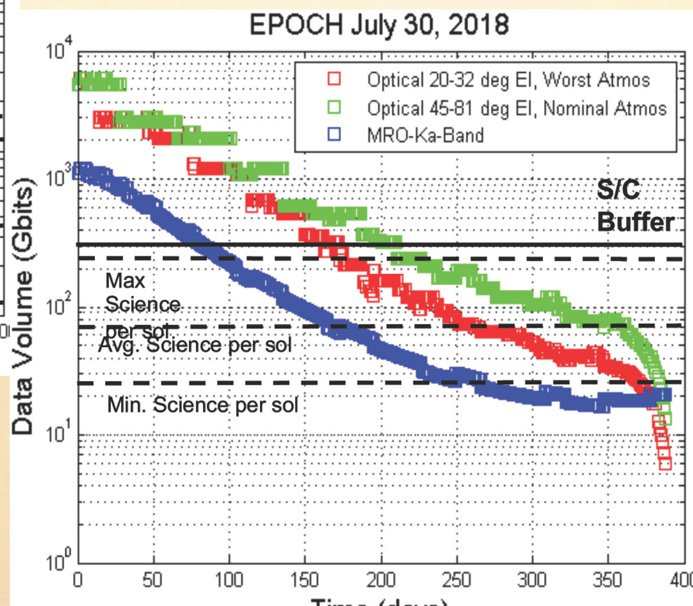
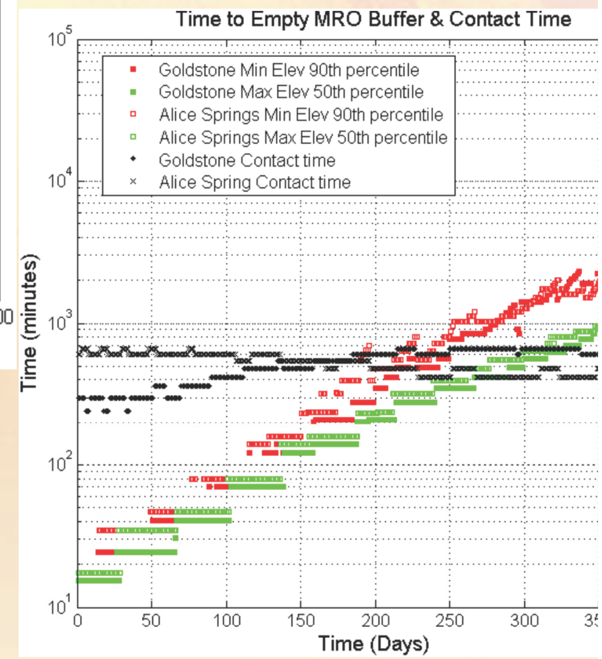
Mars Mission Example



GOLDSTONE, California



ALICE SPRINGS, Australia



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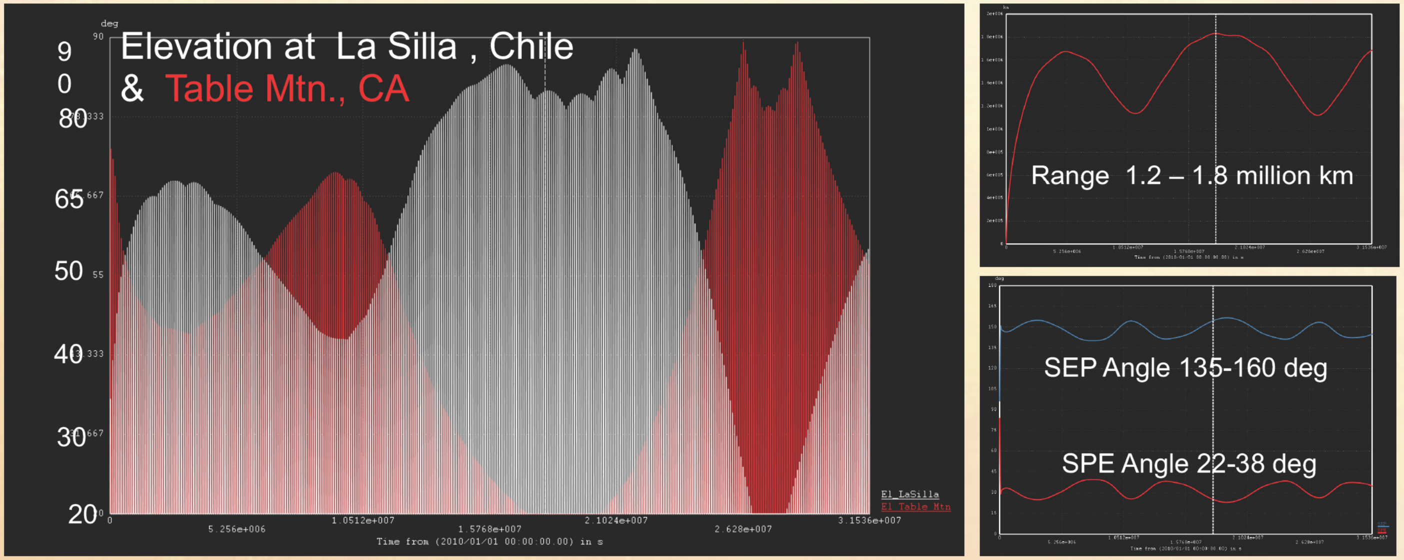
Astrophysics Mission Example

- **Astrophysics missions project 1.5 Gb/s instantaneous data-rates**
  - 6 Tbyte per day science data volume & 12 Tbyte on-board storage
- **North and South Hemisphere ground stations required for servicing mission**



Optical technology available for servicing future astrophysics missions requiring 10x JWST data volumes

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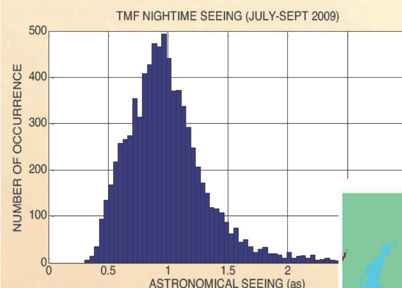
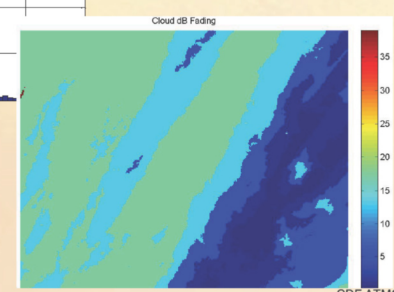
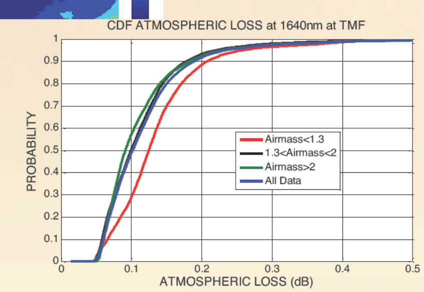
Operating a Suite of Atmospheric Data Gathering Instruments

- **Sun Photometer:** **Atmospheric transmittance & daytime sky-radiance**
- **IR Cloud Imager:** **Thermal infrared image of cloud**
- **DIMM Instrument:** **Nighttime atmospheric turbulence measurements**
- **Solar DIMM:** **Measures r_0 while looking at Sun**
- **Scintillometer:** **Atmospheric turbulence at ground layer**
- **Particle Profiler:** **Measures aerosol content in atmosphere**







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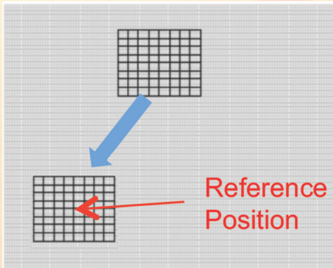
Time-Domain Simulation Summary

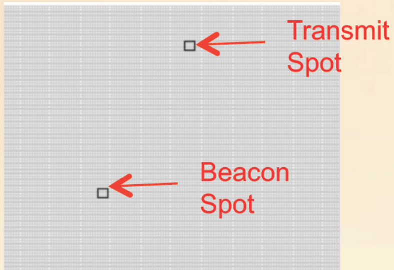
- **Developed strategy to simulate beacon acquisition from space with**
  - "Blind pointing" in presence of base-body disturbance (MRO disturbance spectrum)
  - Uses mechanical transfer functions for struts, sensors and actuators
  - Includes beam scintillation after multi-beam averaging
  - Uses photon counting detector array and read-out models developed by DOT Technology Program
- **Acquisition is divided into 3-modes**
  1. 64 uniformly spaced 4×4 windows with sampling time of 0.01s are assumed
     - Introduce a spiral scan and together with beacon motion spot will intersect one of the 4×4 "active regions" at which time
     - centroid estimate is made
  2. Group and connect 4×4 windows, improve centroiding estimates at 100 Hz update, initiate control loop and steer beacon spot to reference position
  3. Collapse beacon sampling to 4×4 pixel and initiate centroiding on the transmit laser spot with centroid estimate updates on both the spots at 100 Hz

Mode 1: 64 4×4 "active" regions over 128 × 128 focal plan array

Mode 2: Following initial detection control beacon and move to reference position



Mode 3: Following initial detection control beacon and move to reference position



This tool shortens time to assert beacon sense flag and initiate control

- Alternative strategy of reading out full frame would take 1s making acquisition marginal

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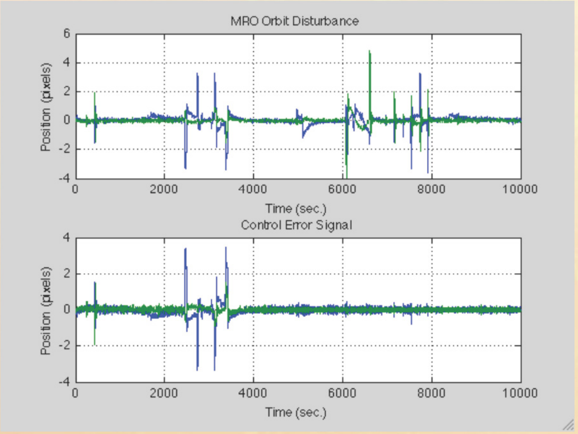
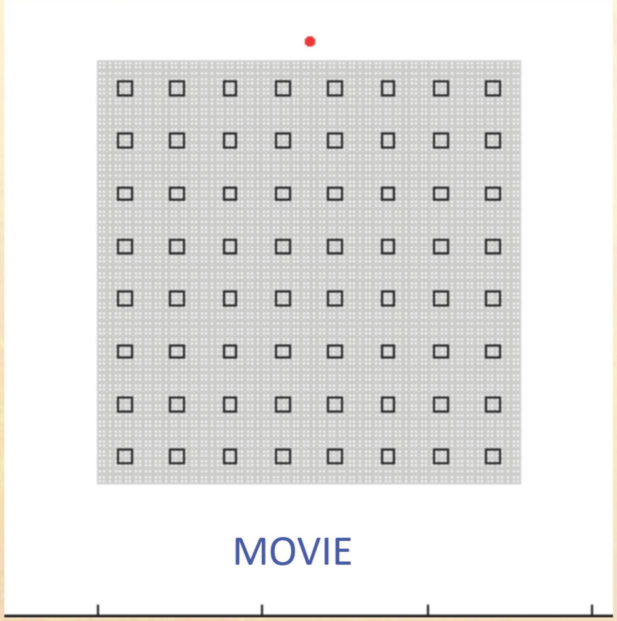
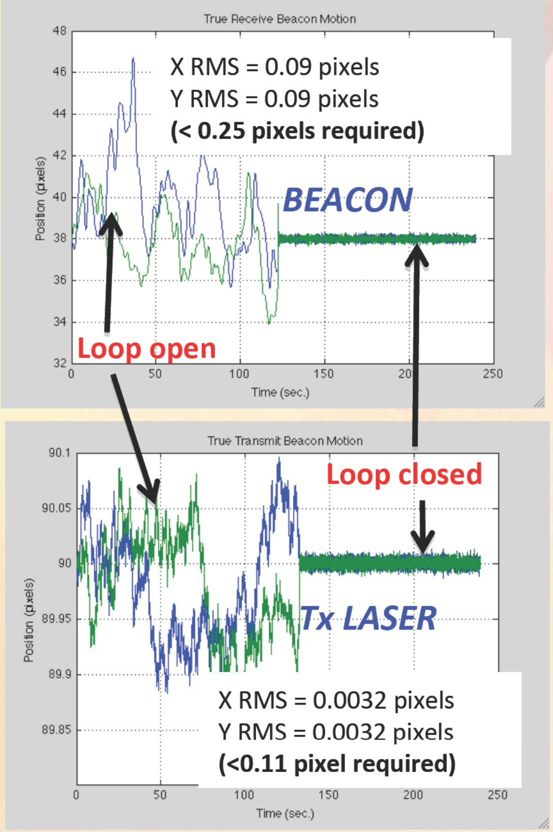
Time Domain Simulation (cont.)

- **Determined focal plane trajectories of beacon in presence of disturbance with a simplified 1D model for the isolation platform**
  - **For worst case signal and beacon at Mars farthest distance**

MRO DISTURBANCE







Model's output of closing the loop on the received beacon and the transmit laser spots

<u>Disturbances</u>: MRO orbit disturbance passed through 2nd order isolator Transfer Function with corner of 0.25 Hz, then scaled to pixel space. (8e-6 rad/pixel)
<u>Sensor</u>: Detector sampled at 100 Hz with 4x4 sub windows.
<u>Control</u>: Control loop bandwidths ~ 8 Hz.

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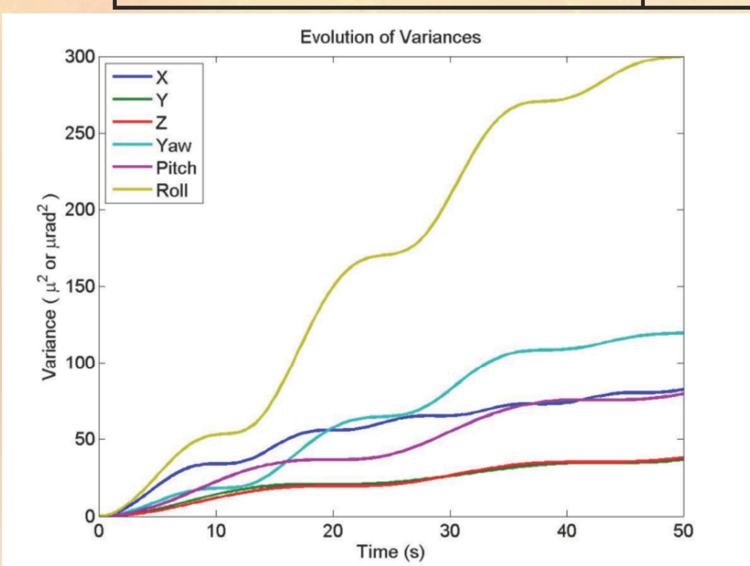
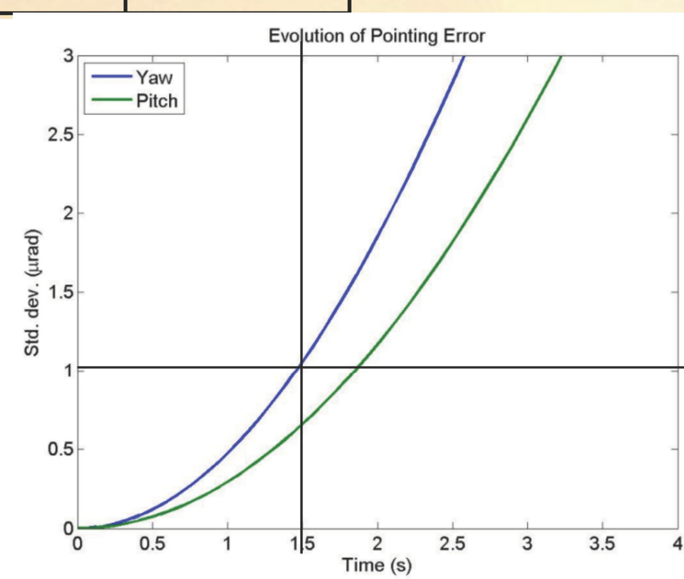
Flywheel Analysis

How long a link can operate without beacon in the event of an interruption?

– **Performed frequency domain modeling to analyze time when allocated downlink pointing error will be exceeded**

	MRO Disturbance	MLCD Disturbance
Fly-wheel Time (s)	1.5	0.35
Fly-wheel time (s) w/active softening of umbilical	4.5	1.5





MRO disturbance analysis example shown below

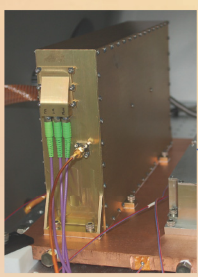
Beacon interruption of >0.5 to 1.5s would require repeating latter stage of beacon spatial acquisition

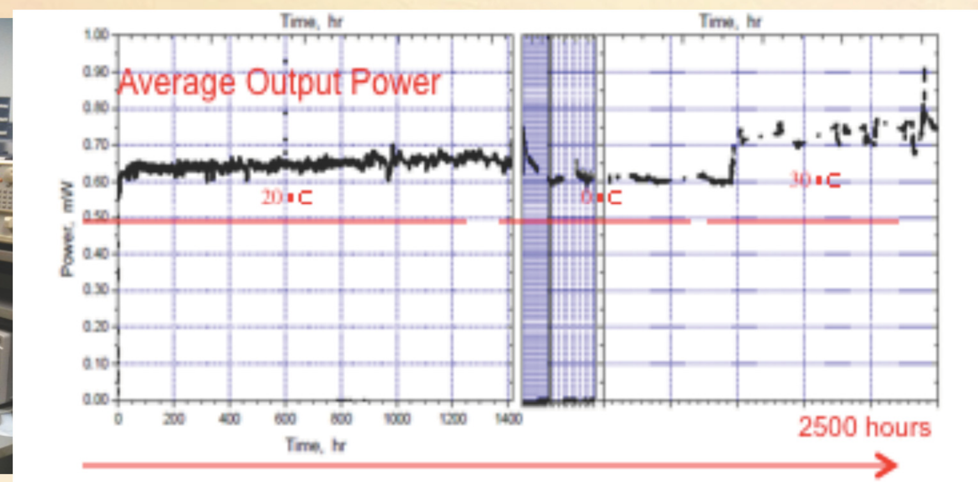
- **Now evaluating Earth centroid tracking to extend allowable outage time**

Qualification of Lasers

- ***Laser Component Qualification***
  - ***Objective:***
    - Demonstrate component reliability with life-test of space grade laser module in simulated space environment
  - ***Results:***
    - >4000h of laser module operation under thermal/vacuum of 0-40˚C, and <10^{-7} Torr
      - 1550nm seed laser, fiber pre-amplifier and pump diodes, external modulator, RF drive electronics,
      - Experienced early degradation of fiber amplifier under vacuum traced to mechanical robustness of encapsulated fiber – reworked by manufacturer

Laser Life – Test Station





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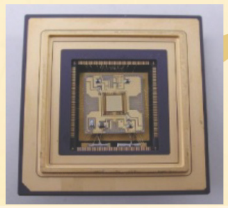
Deep Space Optical Transceiver Development

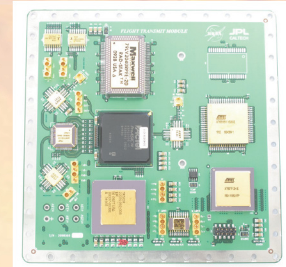
Photon Counting Space Receiver

Detector Array

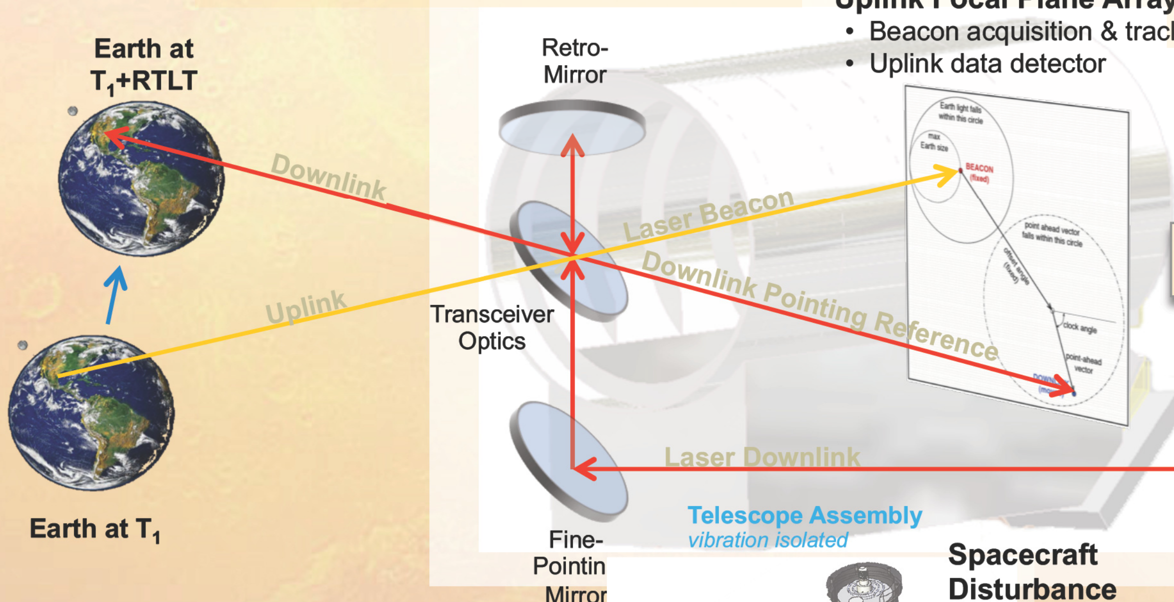


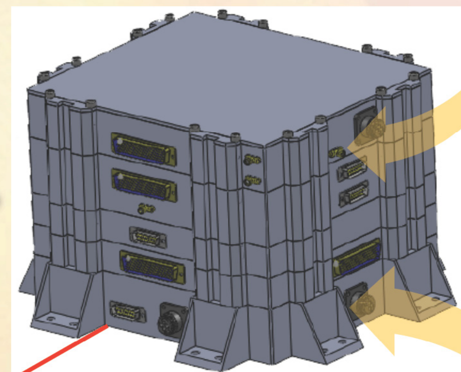
Photon Counting Space Receiver

Simulation, Brassboard & Testbed



Uplink Focal Plane Array
- Beacon acquisition & tracking
- Uplink data detector

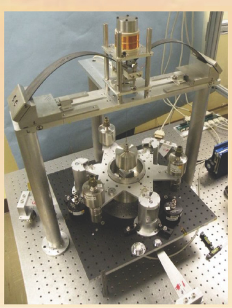


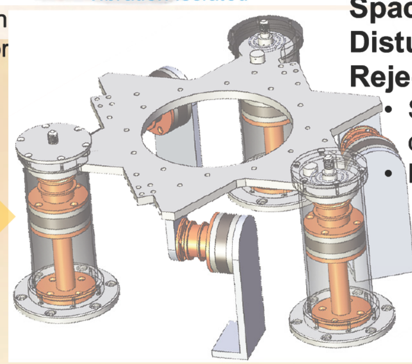


Laser & Electronics Assembly
not vibration isolated

Spacecraft Disturbance Rejection Platform

Low-Frequency Vibration Isolation Platform & Test Facility

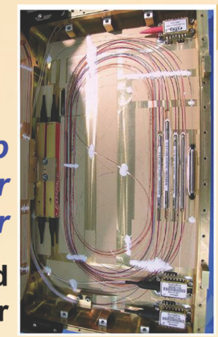




Spacecraft Disturbance Rejection Platform
- Spacecraft disturbance isolation
- Boresight pointing

Efficient Deep Space PPM Laser Transmitter

1530 nm - Pumped PPM Laser Amplifier



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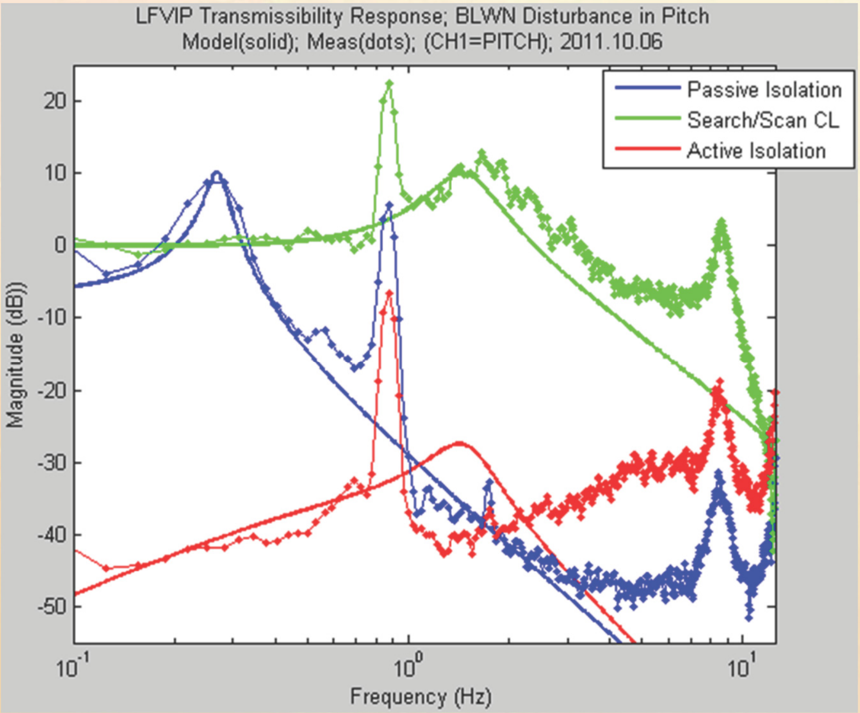
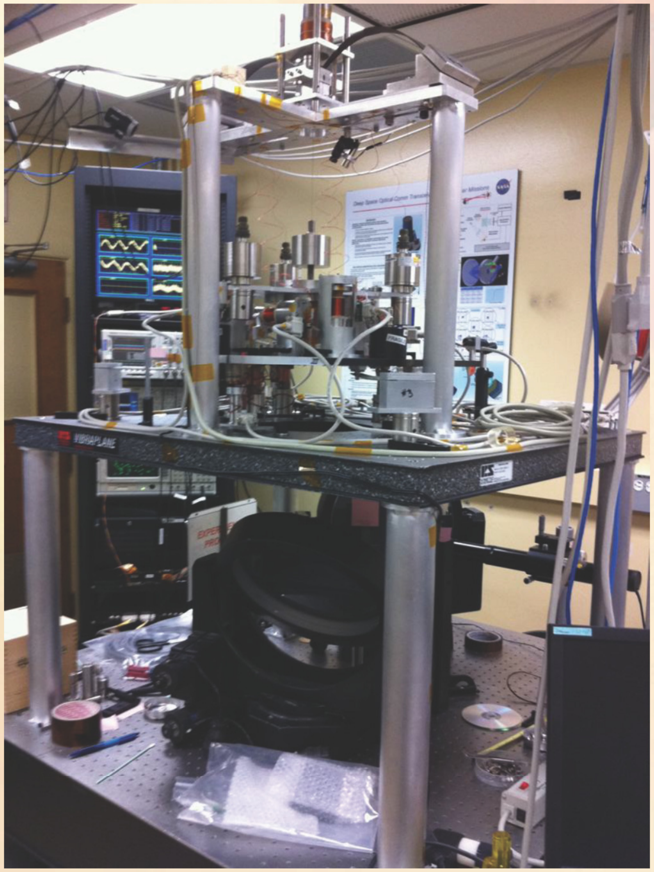
Spacecraft Disturbance Rejection Platform





Low Frequency Vibration Isolation Platform (LFVIP) & Test Facility

>40dB rejection of frequencies down to 0.1 Hz with a hybrid of passive and active isolators

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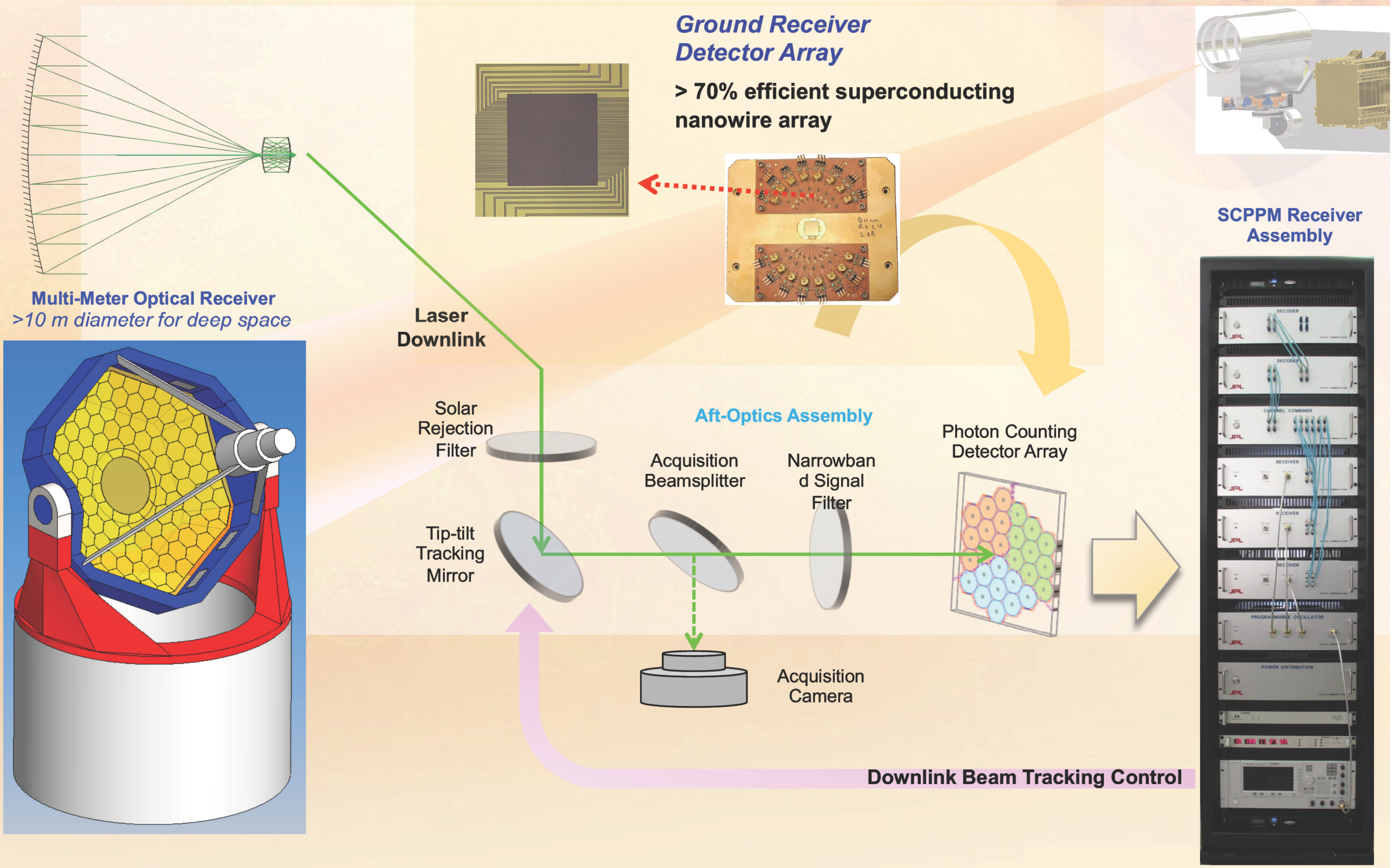
Multi-Meter Optical Receiver Developmen



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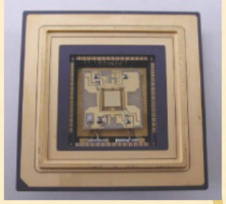
Overall Scope of Technology Development

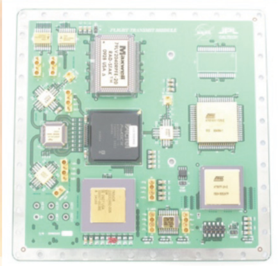
Photon Counting Space Receiver

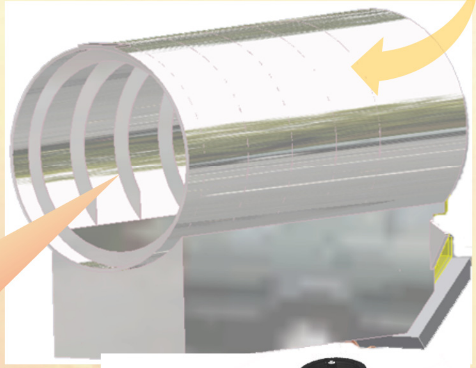
Detector Array

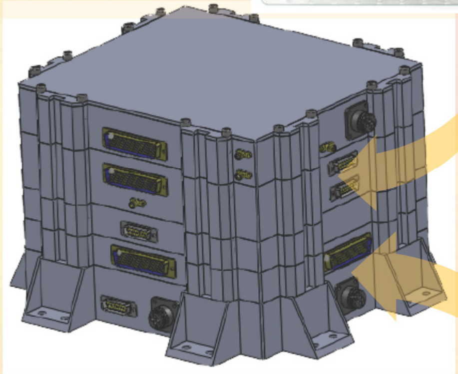


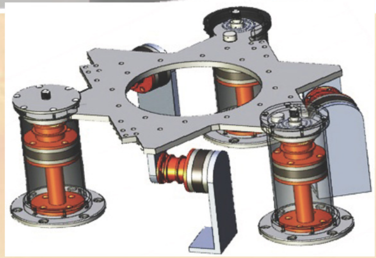
Photon Counting Space Receiver

Simulation, Brassboard & Testbed



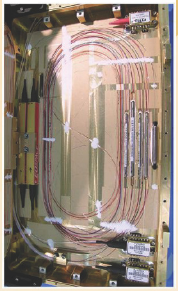


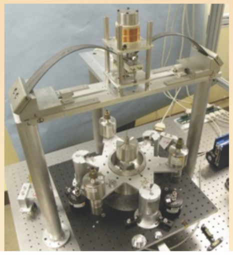




Efficient Deep Space PPM Laser

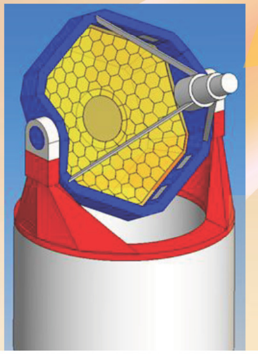
1530 nm - Pumped PPM Laser Amplifier





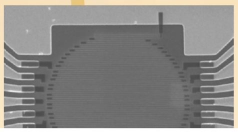
Spacecraft Disturbance Rejection Platform

Low-Frequency Vibration Isolation Platform & Test Facility



Ground Receiver Detector Array

> 70% efficient superconducting



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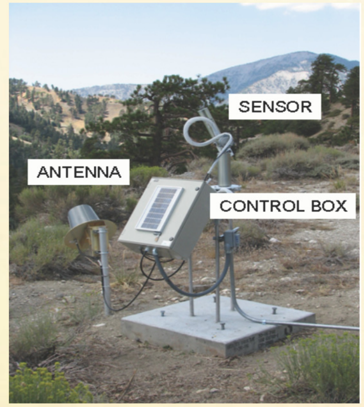
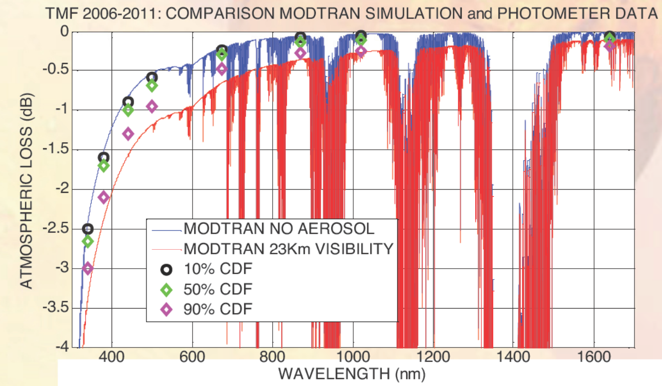
Atmospheric Data Gathering

Sun Photometer

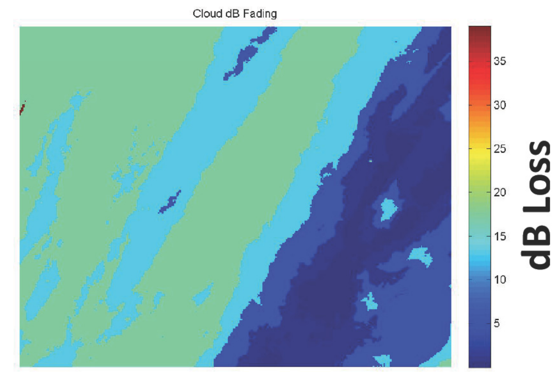
- Completely autonomous
- Atmospheric **transmittance** and **sky radiance** at different wavelengths
- Every 15 minutes: data collected
- Every 60 minutes: data transmitted to NOAA via geo-stationary spacecraft





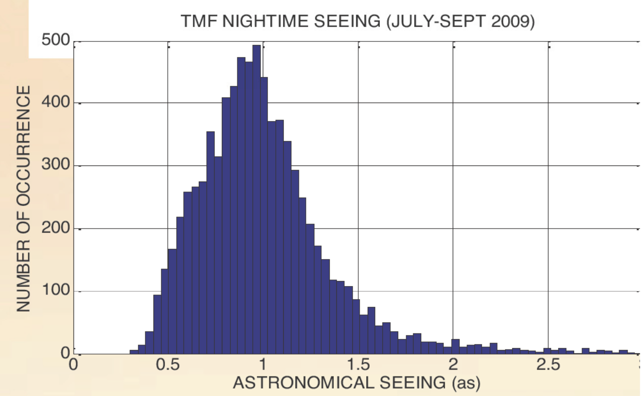
Infrared Cloud Imager

- 60° field-of-view
- Takes/stores radiometrically-calibrated images of the sky every 5 minutes
- Thin clouds absorption loss are displayed in real time

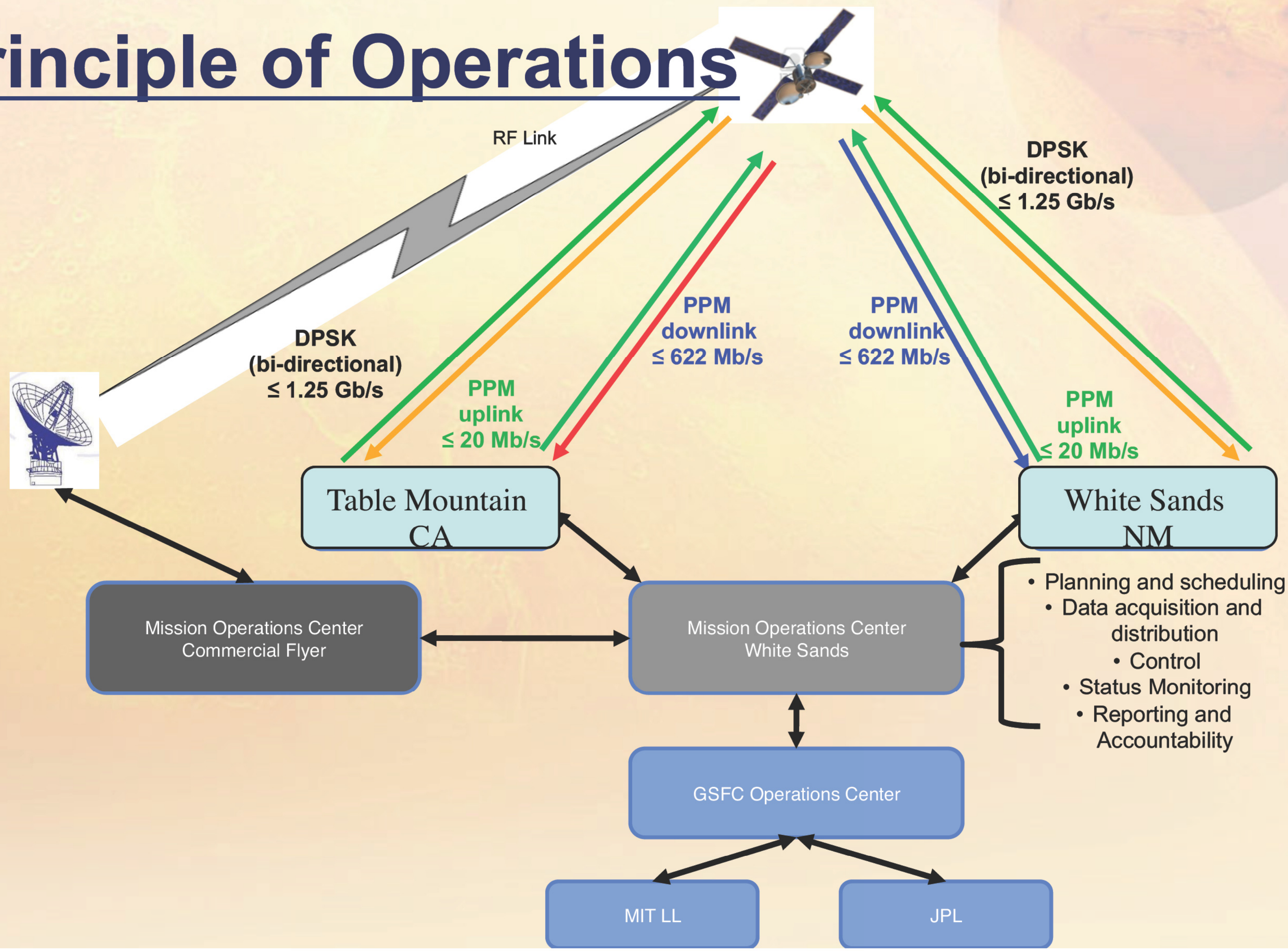


DIMM *(Differential Image Motion Monitor)*

- Night-time & daytime seeing monitor
- Astronomical seeing is derived from measurements of the RMS of the centroid motions of the double images of a star, and sun (for daytime).



Principle of Operations



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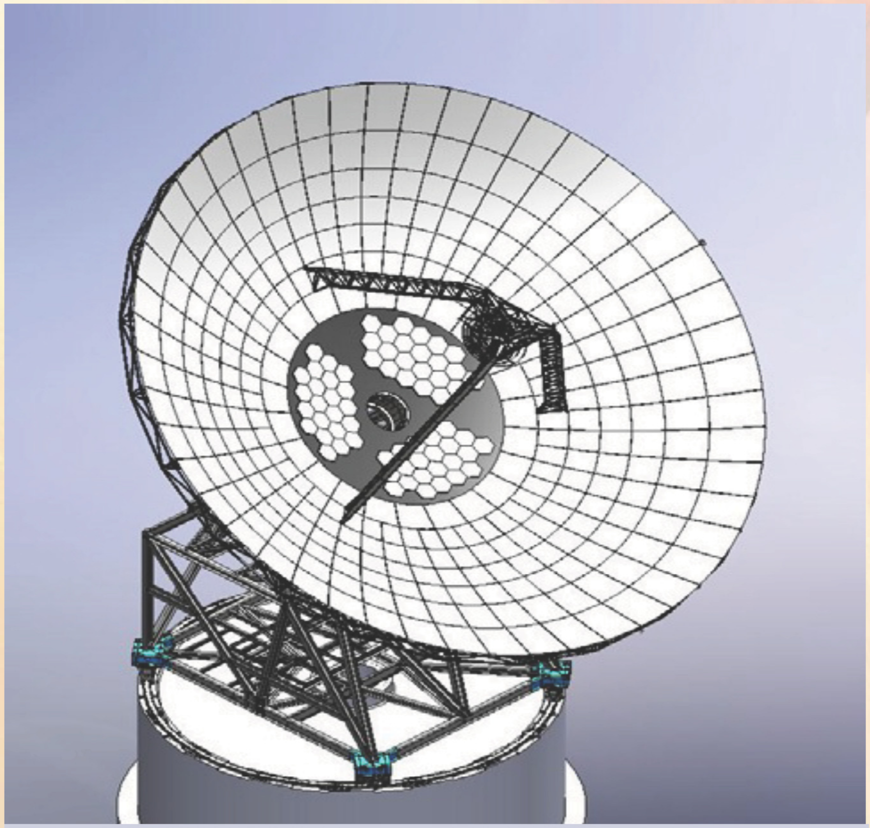
Hybrid Ground Station For RF and Optica Communications

- Developing a hybrid ground station capable of simultaneously supporting RF & optical comm for deep space application

- **To reduce development and operational cost, the design for the existing 34-m RF antennas is used**
  - Optical capability may be added to the existing RF capability

- **Demonstration platform is NASA's existing experimental 34m antenna**

- **Optical Specifications**
  - Operational wavelength (λ): 1550nm
  - Optical signaling format: PPM
  - Receiver surface quality: <1λ



Central part of the antenna dish is modified to collect optical signals

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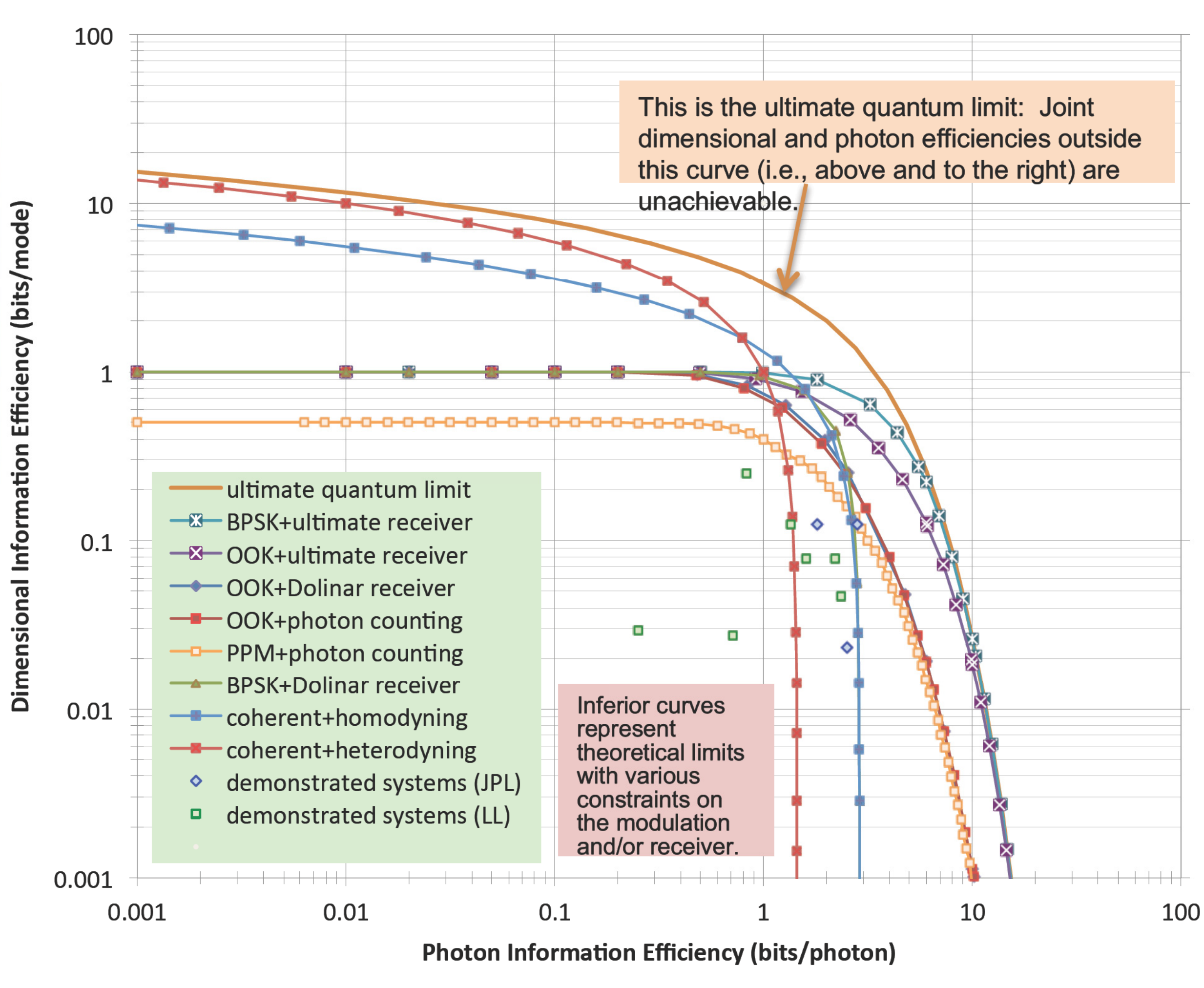
Highly Efficient Data Detection

Fundamental free-space capacity limits vs. state-of-the-art optical systems

Goal: 10 bits/photon detection

Demonstrated 7 bits/photon in the laboratory, so far




QUESTIONS?